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To: Commissioner of Patents

From: Stephen B. Ackerman Reg. No. 37, 761
28 Davis Avenue
Poughkeepsie, NY 12603

Re: Serial No. **10/764,914**
Filing Date: **01/26/04**
Invr(s): **Sibrai, et al**
Title: **High Q Linear Controlled Variable Capacitor Using Translinear Amplifier**

Please enter the enclosed Certified Copy of European patent application number 04368004-0 (filed on January 14, 2004) in the file for the above-referenced US patent application, which claims priority to this European patent application.

Respectfully submitted,

Stephen B. Ackerman
Reg. No. 37,761

CERTIFICATE OF MAILING

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Signature ____________________ Date: May 11, 2004
Stephen B. Ackerman Reg. No. 37,761

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Dialog Semiconductor GmbH
Neue Strasse 95
73230 Kirchheim/Teck-Nabern
ALLEMAGNE

Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

High Q linear controlled variable capacitor using translinear amplifier

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Bescheinigung

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Attestation

Die angehefteten Unterlagen stimmen mit der ursprünglich eingereichten Fassung der auf dem nächsten Blatt bezeichneten europäischen Patentanmeldung überein.

The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

04368004.0

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

High Q linear controlled variable capacitor using Translinear Amplifier

Technical field

The invention relates to a voltage controlled variable capacitor, and more particularly, to a variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, which are typically integrated with the capacitance controlling functions on an integrated semiconductor circuit.

Background art

One example of a voltage-controlled capacitor is a varactor diode. When a reverse voltage is applied to a PN junction, it creates a depletion region, essentially devoid of carriers, which behaves as the dielectric of a capacitor. The depletion region increases as reverse voltage across it increases; thus the junction capacitance will decrease as the voltage across the PN junction increases. However the characteristics are non-linear and are widely temperature and process dependent. There is also a significant leakage current problem. Varactor diodes must be operated below the junction breakdown voltage. The varactor diode is sometimes called a varicap.

Fig. 1a shows the principle of a varactor diode; Fig. 1b shows the control voltage to capacitance characteristics of said varactor diode and demonstrates the effects of temperature and process variations. Another example is a switched capacitor chain, where capacitors are switched in parallel one after the other, thus increasing the capacitance step by step. The capacitors, when made of metal or polycarbonate structures, are far less sensitive to temperature and process deviations.

Fig. 2a shows the basic circuit concept. However, as is demonstrated in Fig. 2b, there is only a "step-wise linear" capacitance change over the control voltage. In addition the switching of the individual capacitors causes switching noise ("spikes") on the common circuit rails. Furthermore, while the switching transistor is kept in flat switching ramp to smooth the switching steps, the transistor's resistance causes a Q-factor problem.

U.S. Patent 6,356,135 (to Rastegar) describes an electronically trimable capacitor having a plurality of branch circuits, each including a capacitor which may be selectively controlled by a switch to contribute or not to the net capacitance exhibited by the trimable capacitor. Operation of the switches is under direction of digital instruction.

U.S. Patent 5,514,999 (to Koifman , et al.) shows a differential switched capacitor circuit, comprising: multiple switched capacitor stages, coupled in a chain.

U.S. Patents 4,449,141 and 4,456,917 (to Sato, et al.) disclose a variable capacitor comprising a plurality of variable capacitor elements each having depletion layer control sections and a capacity reading section formed on a semiconductor substrate so that the capacity appearing at each capacity reading section varies in response to the bias voltage applied to the depletion layer control sections.

Summary of the invention

A principal object of the invention described in the present document is to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

The basic aspects of a mechanism to linearly control the capacitance of a variable capacitor in a linear mode through a tuning voltage are described in a related patent application. This related patent application, which is entitled " High Q linear controlled variable capacitor " (Document Nr. DS03-005A), is hereby incorporated by reference.

In accordance with the objectives of this invention, a circuit to implement a voltage controlled variable capacitor, operating in a linear mode and maintaining High Q-Factor is achieved. The invention disclosed in the referenced document DS03-005A added circuits and methods to linearize the capacitance change and to minimize the effect of parasitic resistance in the capacitor switching elements, which would degrade Q-factor. The herewith disclosed invention further implements a translinear amplifier and adds additional circuits to further reduce the effect of parasitic resistance and of temperature deviation.

One key point to obtain highest possible Q-factor is to have at any time only one transistor in the active operating mode, i.e. RDSon–change-mode; all other transistors are either fully switched on or fully switched off.

Key element to achieve the goal of the invention is the introduction of a translinear amplifier into the signal path. Furthermore, functions to limit the switching-signal in order to drive the capacitor-switching element, typically a FET-transistor, into minimum RDSon or maximum RDSoff are added. Even further, a circuit to compensate the temperature effect of the capacitor switching device is added.

The translinear amplifier, typically with a gain of 1, compares a differential voltage at its inputs and provides the same differential voltage at its outputs; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, independent of the absolute voltage level at the outputs; input and output are perfectly decoupled. Said translinear amplifier can operate at different absolute voltage levels at their input and work independent at an output level, best suitable for said switching transistor's operation.

While the switching transistor is kept within its active switching mode (RDS changing mode) the resistance of the transistor linearly follows the input difference of said translinear amplifier. As said translinear amplifier can operate at different absolute voltage levels at their input and output, the resulting level shifting operation is best suitable for said switching transistor's operation.

Additional circuit elements, described in the companion disclosure Document DS03-006, implementing a signal-limiting function, drive said switching transistor either into its fully-on state (RDSon going to 0) or drive it into its fully-off state (RDSoff going very high) when said switching device is outside its dedicated active working area.

There are various techniques to generate a set of reference values defining the threshold points for each of said amplifier stages. And there are various techniques to provide a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

The total concept according to the proposed invention is shown in Fig. 6. One key point of the invention is the implementation of a signal-limiting function at both ends of the active switch operating area. Once the signal controlling the switching device leaves the dedicated active area, the signal condition is changed abrupt. Fig. 7 visualizes this effect. The purpose is to drive said switching device to a fully-on state, when said switching device is outside its dedicated active working area on the lower resistance side and to drive said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side.

Depending on the technique to implement the reference values for each of the amplifiers within said translinear amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could, for example, be discrete metal

or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET or a CMOS FET.

The amplifier primarily generating the control signal for the switching devices is, according to the invention, a translinear amplifier. In addition, a signal-limiting function, which is designed to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side or to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side, can be implemented. Such signal-limiting function could, according to the invention, be implemented within the translinear amplifier. It could however be implemented as separate circuit as well.

The circuit also provides the components to generate the set of reference voltages for the threshold voltages of each amplifier stage. A resistor chain is one possible solution. The amplifiers then use the tuning voltage supplied and said reference voltages to generate the control signal for said switching devices, which then switch the capacitors in parallel, one after the other.
Furthermore, the temperature deviation, caused by the temperature characteristics of the switching device can be compensated. One concept is to use a device of the identical type of the switching device to produce a temperature dependent signal and feed it as compensating voltage into the output reference point of the translinear amplifier. This will mirror the exact equivalent of the temperature error into the switching control signal and compensate its temperature error.

Even further, a specific non-linear characteristic of the tuning voltage to capacitance relation can be achieved by dimensioning the relation between said tuning voltage and said threshold points as desired. In one proposed solution, the individual steps of the reference resistor chain will be dimensioned to the desired nonlinear curve.

A translinear amplifier typically has a gain of 1. However, a gain different from 1 is also achievable, which, if implemented, gives one more degree of freedom in dimensioning the circuit parameters. For example, the remaining overlapping of neighboring capacitor switching stages may be even further reduced.

In accordance with the objectives of this invention, a method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate, is achieved. One method is to switch a variable number of capacitors in parallel, where only one is in the active transition phase of being switched on in a continual mode. All other capacitors of a larger number of capacitors are either already fully switched on or are still complete switched off. One key method is to linearly control the switching function for each of said continual switching devices, when said switching device is in its dedicated active working area in a linear mode, but to change the signal abrupt, as soon as the control signal for said switching function leaves its dedicated active working area. One method drives said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side. A similar method drives said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side. A further method amplifies, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the reference voltage of each amplifier stage, producing the linear control signal for said continually switching operation. Another method generates a set of reference values, one for each of said amplifier stages. Finally, the circuit supplies a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

A further method compensates the temperature effect of the switching device. It generates a temperature dependent compensation voltage by using an identical device-type as the switching device and feeds the resulting signal into the output reference point of the translinear amplifier

An even further method is to produce threshold points (or reference points) along a non-linear curve and getting a desired non-linear relation of the total capacitance changes versus tuning voltage.

Even more, with a translinear amplifier with a gain different from 1, the whole concept gains one more degree of freedom in optimizing certain operating parameters, like the overlapping of neighboring switching stages.

Description of the drawings

In the accompanying drawings, forming a material part of this description, there is shown:

Fig. 1a (Prior Art) shows a simplified structure of a varactor diode.

Fig. 1b (Prior Art) shows the relation of the capacitor over tuning voltage change and shows the effects of temperature and process variation.

Fig. 2a, and 2b (Prior Art) shows a principal circuit of a switched capacitor chain and the relation of the capacitor over tuning voltage change.

Fig. 3 shows a circuit with operational amplifiers in the control signal path and with a chain of resistors as reference voltage circuit.

Fig. 4a shows the gate voltage versus tuning voltage relation for the series of capacitor switching stages, according to Fig. 3.

Fig. 4b visualizes the signal overlapping effect of the switching operations of just 2 stages of the circuit according to Fig. 3.

Fig. 5 shows the principal circuit arrangement of a single capacitor switching stage with a translinear amplifier.

Fig. 6 shows the circuit schematic of multiple capacitor switching stages with a chain of translinear amplifiers, in accordance with an embodiment of this invention.

Fig. 7 visualizes said switching transistor's gate voltage versus capacitor tuning voltage dependency of a single stage.

Fig. 8 visualizes said switching transistor's gate voltage, versus capacitor tuning voltage dependency of a multiple stages.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention.

Fig. 10 shows the added circuit to generate a temperature compensated reference voltage.

Fig. 11a demonstrates the resulting capacitance versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 11b demonstrates the resulting Q-factor versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 12 demonstrates 2 possible variations of capacitance versus tuning voltage characteristics.

Fig. 13 visualizes the methods to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and achieving a high Q-factor.

Description of the preferred embodiments

The objectives of this invention are to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

A discussion of the general principles of a voltage controlled variable capacitor with linear characteristic, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, using operational amplifiers is disclosed in the related patent application DS03-005A, the entire contents of which is incorporated herewith by reference.

Fig. 3 shows a principal circuit diagram of the referenced related patent application. Amp 1 to Amp n are said operational amplifiers, Sw 1 to Sw n are the switching devices and Cap 1 to Cap n are said capacitors that will be switched in parallel. As an example, a resistor chain R1 to Rn, or a similar circuit, produces a series of voltage references Ref 1 to Ref n and each of said operational amplifiers compares the tuning voltage input with its dedicated reference voltage. The resulting variable capacitance is available at the output points varCap.

A detailed view on the individual ramp-up functions at the switching transistor's gate, of the circuit according to Fig. 3, is shown in Fig. 4a. Vg1 to Vg7 are the gate voltage versus tuning voltage slope of the switching stages number 1

to 7 in this example. One can assume the active area of RDS changing to be between the 2 % point and the 98 % point. All slopes of the individual gate voltages are strictly parallel. Threshold points Th1 to Th7 in Fig. 11 are equally spaced (distances d1 to d7 in Fig. 4a). Fig. 4b visualizes the overlapping switching operations of just 2 adjacent stages of the circuit according to Fig. 3. Overlap is a measure, where Vg2 just starts to switch on stage number 2 and where Vg1 is still in the active working range for stage number 1. Because said gate voltage versus tuning voltage slopes are all in parallel, all overlaps are the same.

According to the objectives of this invention, the operational amplifiers as shown in Fig. 3, are replaced by translinear amplifiers. A single stage of said capacitor switching function is presented in Fig. 5 and the total circuit schematic for multiple stages according to the proposed invention is shown in Fig. 6. Key advantage is the fact, that the voltage levels at the translinear amplifier inputs and at the translinear amplifier outputs are independent, only the differential voltage at the inputs and at the outputs is important. It works in this context as a level shifter. Such translinear amplifiers have typically a gain of 1.

The translinear amplifier in Fig. 5 compares the differential voltage at its inputs Vinp-5 and Vinn-5 and, through various current mirroring techniques, provides the same differential voltage at its outputs Voutp-5 and Voutn-5; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, independent of the absolute voltage level at the outputs. The translinear amplifier then drives said current switching device N1-5 with the gate voltage Vg-5 to linearly switch on said individual small capacitor Cap-5.

Within a chain of said translinear amplifiers, each one can operate at a different absolute voltage level at their input and work independent at another output level. In this way the network to generate the reference voltages can be optimized independently for each stage, because the voltage level best suitable for the control operation of each switching transistor can be freely selected. In the circuit shown in Fig. 6 as an example, the reference voltages are produced in a

simple chain of resistors. The translinear amplifiers Tr.Amp 1 to Tr.Amp n can adjust between said input reference voltage levels Ref-in 1 to Ref-in n and the output reference levels Ref-out-1 to Ref-out-n. Said translinear amplifiers then control the switching transistors Sw 1 to Sw n, which in turn linearly switch on the individual small capacitors Cap 1 to Cap n.

Another key point of the invention is the implementation of a signal-limiting function at both ends of the active switch operating area. As long as the switching transistor is kept within its active switching mode (RDS changing mode) the resistance of the transistor linearly follows the input difference of said translinear amplifier. Once the signal controlling the switching device leaves the dedicated active area, the signal condition is changed abrupt. Fig. 7 visualizes this effect. The purpose is to drive said switching device to a fully-on state, when said switching device is outside its dedicated active working area on the lower resistance side and to drive said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side. Additional circuit elements, implementing said signal-limiting function, drive said switching transistor either into its fully-on state (RDSon going to 0) or drive it into its fully-off state (RDSoff going very high) as soon as said switching device falls outside its dedicated active working area. Such signal-limiting function could, according to the invention, be implemented within said translinear amplifier circuit. It could however be implemented as separate circuit external to said translinear amplifier as well.

Fig. 7 visualizes the idea of sharply cutting off said signal controlling the switching device as soon as the Gate Control Voltage Vg-7 leaves the dedicated active area, when the Tuning Voltage Vctl changes. For example, beyond the 98 % on-point, said signal Vg-7 controlling the switching device rises sharply and below the 2 % off-point said signal Vg-7 controlling the switching device is driven to rapidly switch-off. Fig. 8 presents the same behavior as Fig. 7 for a larger number of said capacitor switching stages. Th1 to Thn are the selected threshold points for said switching to occur. d1 to dn are the distances of said threshold points, that normally are dimensioned to equal distance.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention. Tr.Amp 1 to Tr.Amp n are said translinear amplifiers, Sw 1 to Sw n are the switching devices and Cap 1 to Cap n are said capacitors that will be switched in parallel, resulting in the total capacitance varCap. R1 to Rn build the resistor chain to produce references voltages for the amplifier of each stage, as already shown in Fig. 6.

Furthermore, a concept of this disclosure is to compensate the temperature deviation, caused by the temperature characteristics of the switching device; Fig. 10 presents this concept. One method is to use a device N2-10 of the identical type of the switching device N1-10 to produce a temperature dependent signal and feed it as compensating voltage Vref-10 into the output reference point Voutn-10 of the translinear amplifier. This will mirror the exact equivalent of the temperature error into the switching control signal Vg-10 and compensate its temperature error.

The total capacitance versus tuning voltage characteristic for a circuit with n-stages is demonstrated in Fig. 11a and the overall characteristic of said Q-factor is presented in Fig. 11b

Depending on the technique to implement the reference values defining said threshold points for each of the amplifiers within said translinear amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed. The concept is demonstrated in Fig. 12, with Curve A and Curve B as examples.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The advantage of a capacitor not being of the junction (diode) type capacitor is the invariance due to voltage or temperature at the capacitor. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET or a CMOS FET. In the case

complementary components are used all voltage levels would just be inverted without changing the principals of operation.

The method to achieve the objectives of this invention is illustrated in Fig. 13. First (80), it starts with just the first capacitor, i.e. the count n=1 (81). When the tuning voltage is rising (82) or is high enough (83), the amplifier ramps up (85) and the switching device linearly switches on capacitor element n (87). If the tuning voltage continues to rise (90) the amplifier continues to ramp up (91). If however the tuning voltage turns down (90), the amplifier will ramp down as well (92). Once the tuning voltage reaches the upper limit of the active switching area (95), the switching device of stage n is fully switched on (97) and the process continues with the next step n = n + 1 (99)(101). Depending on the direction of continued voltage change (103) it continues to ramp up or down. In case tuning voltage is lower than maximum for stage n (84), the amplifier ramps down (86) and the switching device linearly switches on capacitor element n (88). Once the tuning voltage reaches the lower limit of the active switching area (96), the switching device of stage n is fully switched on (98) and the process continues with the next step n = n + 1 (100)(102). Again, depending on the direction of continued voltage change (103) it continues to ramp up or down and restarts at (82).

CLAIMS

1. A circuit to control the capacitance of a variable capacitor in a strictly linear mode through a steady tuning voltage and to achieve a high Q-factor at the same time; comprising:

- means for a set of individual small capacitors;
- means for a set of switching devices to continually switch on each capacitor of said set of capacitors in parallel;
- means to linearly control the switching function for each of said set of continuous switching devices;
- means for a set of translinear amplifier stages to produce said linear controls for said switching functions;
- means to individually provide the threshold points for each individual capacitor switching stage; and
- means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

2. The circuit of claim 1 wherein said switching device is a transistor.

3. The circuit of claim 2 wherein said switching device is a P-MOS or N-MOS junction FET.

4. The circuit of claim 2 wherein said switching device is a CMOS FET.

5. The circuit of claim 1 wherein said translinear amplifier has a gain differing from 1, which gives one more degree of freedom to optimize operating parameters, like overlapping of capacitor switching operation.

6. The circuit of claim 1 wherein said means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, is a single signal connected to all amplifier inputs.

7. The circuit of claim 1 wherein the means to provide the output reference signal for the translinear amplifier, is a single signal connected to all translinear amplifier reference outputs.

8. The circuit of claim 1 wherein said capacitors are integrated on a semiconductor substrate, but on a separate substrate than said switching devices and amplifiers.

9. The circuit of claim 1 wherein said capacitors are integrated on a semiconductor substrate and on the same substrate as said switching devices and amplifiers.

10. The circuit of claim 1 wherein said capacitors are manufactured as a Metal-Oxide structure or as a junction capacitor.

11. A circuit to control the capacitance of a variable capacitor in a strictly linear mode through a steady tuning voltage and to achieve a high Q-factor at the same time by sharply cutting off the control signal, when said switching device is outside its dedicated active working area; comprising:

- means for a set of individual small capacitors;
- means for a set of switching devices to continually switch on each capacitor of said set of capacitors in parallel;
- means to linearly control the switching function for each of said set of continuous switching devices, when said switching device is in its dedicated active working area;
- means to drive said switching device to a fully on status, when said switching device is outside its dedicated active working area on the lower resistance side.
- means to drive said switching device to a fully off status, when said switching device is beyond its dedicated active working area on the higher resistance side.
- means for a set of translinear amplifier stages to produce said linear controls for said switching functions;
- means to individually provide the threshold points for each individual capacitor switching stage; and

- means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

12. The circuit of claim 11 wherein said means to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side is provided by additional circuit elements, working as a signal-limiting function.

13. The circuit of claim 11 wherein said means to drive said switching device to a fully-off status, when said switching device is outside its dedicated active working area on the higher resistance side is provided by additional circuit elements, working as a signal-limiting function.

14. The circuit of claim 12 wherein said signal-limiting function to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side, are implemented within the translinear amplifier circuit.

15. The circuit of claim 13 wherein said signal-limiting function to drive said switching device to a fully-off status, when said switching device is outside its dedicated active working area on the higher resistance side, are implemented within the translinear amplifier circuit.

16. The circuit of claim 1 or 11 wherein said translinear amplifier has a gain of 1, the typical gain of translinear amplifiers.

17. The circuit of claim 11 wherein said translinear amplifier has a gain differing from 1, which gives one more degree of freedom to optimize operating parameters, like overlapping of capacitor switching operation and signal cut-off at the edges of the dedicated active working area.

18. The circuit of claim 1 or 11 wherein said capacitors are discrete capacitor components.

19. The circuit of claim 1 or 11 wherein said capacitors are manufactured on a planar carrier.

20. A circuit to control the capacitance of a variable capacitor in a strictly linear mode through a steady tuning voltage and to achieve a high Q-factor at the same time and to compensate the temperature deviation of the capacitor switching device; comprising:

- means for a set of individual small capacitors;
- means for a set of switching devices to continually switch on each capacitor of said set of capacitors in parallel;
- means to linearly control the switching function for each of said set of continuous switching devices;
- means for a set of translinear amplifier stages to produce said linear controls for said switching functions;
- means to compensate the temperature deviation of said switching device;
- means to individually provide the threshold points for each individual capacitor switching stage; and
- means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

21. The circuit of claim 20 wherein said means to compensate the temperature deviation of said switching device is provided by feeding a modified reference voltage to said translinear amplifier's output reference point, to mirror a temperature correcting signal into the control signal of said switching device.

22. The circuit of claim 21 wherein said means to compensate the temperature deviation of said switching device, uses a device of the same type as said switching device itself, to produce an exact equivalent of said temperature deviation.

23. A circuit to control the capacitance of a variable capacitor in a steady mode, but with predefined non-linear relation to the tuning voltage, through a steady tuning voltage and to achieve a high Q-factor at the same time; comprising:

- means for a set of individual small capacitors;

- means for a set of switching devices to continually switch on each capacitor of said set of capacitors in parallel;

- means to linearly control the switching function for each of said set of continuous switching devices;

- means for a set of translinear amplifier stages to produce said linear controls for each of said set of continuous switching devices;

- means to individually provide the threshold points for each individual capacitor switching stage;

- means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages and;

- means to provide a non-linear relation between said tuning voltage and said threshold points.

24. The circuit of claim 1 or 23 wherein said means to individually provide said threshold points for each individual capacitor switching stage generates a set of reference values, one value for each capacitor switching stage.

25. The circuit of claim 23 wherein said means to provide a non-linear relation between said tuning voltage and said threshold points is provided by specifically selecting the steps of said set of reference values in a way, to achieve said desired non-linear relation.

26. The circuit of claim 24 wherein said means to generate a set of reference values, one for each of said translinear amplifier stages, is implemented as a chain of resistors.

27. A method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time; comprising:

- providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on each capacitor of said set of capacitors

in parallel, means to linearly control the switching function for each of said continuous switching devices, means for a set of translinear amplifier stages to produce said linear controls for said switching functions, means to linearly control said switching function for each of said set of continuous switching devices, means to individually provide the threshold points for each individual capacitor switching stage, means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages;

- continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;

- linearly controlling the switching function for each of said continuous switching devices;

- amplifying, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the threshold points of each amplifier stage to produce the linear control signal for said continually switching operation;

- providing said threshold points for each individual capacitor switching stage; and

- supplying a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

28. The method of claim 27 wherein linearly controlling the switching operation applies to a transistor as said continuous switching device.

29. The method of claim 28 wherein linearly controlling the switching operation applies to a P-MOS or N-MOS junction FET as said continuous switching device.

30. The method of claim 28 wherein linearly controlling the switching operation applies to a P-channel or N-channel CMOS FET as said continuous switching device.

31. The method of claim 27 wherein individually providing said threshold points for each individual capacitor switching stage generates a set of reference values, one value for each capacitor switching stage.

32. The method of claim 31 wherein generating a set of reference values, one for each of said translinear amplifier stages, is performed by a chain of resistors.

33. The method of claim 27 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to discrete capacitor components.

34. The method of claim 27 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to capacitors manufactured on a planar carrier.

35. The method of claim 27 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to capacitors integrated on a semiconductor substrate.

36. The method of claim 27 wherein supplying a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages uses a single signal connected to all amplifier inputs.

37. A method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time by sharply cutting off the control signal, when said switching device is outside its dedicated active working area; comprising:

- providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on said capacitors in parallel, one for each of said small capacitors, means to linearly control the switching function for each of said continuous switching devices, when said switching device is in its dedicated active working area, means to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on

the lower resistance side, means to drive said switching device to a fully-off status, when said switching device is beyond its dedicated active working area on the higher resistance side, means for a set of translinear amplifier stages to produce said linear controls for said switching functions, means to individually provide the threshold points for each individual capacitor switching stage, means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages;

- continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;
- linearly controlling the switching function for each of said continuous switching devices, when said switching device is in its dedicated active working area;
- driving said switching device to a fully on status, when said switching device is outside its dedicated active working area on the lower resistance side;
- driving said switching device to a fully off status, when said switching device is beyond its dedicated active working area on the higher resistance side;
- amplifying, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the threshold points of each amplifier stage to produce the linear control signal for said continually switching operation;
- providing said threshold points for each individual capacitor switching stage; and supplying a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

38. The method of claim 37 wherein driving said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance side uses additional circuit elements, working as a signal-limiting function.

39. The method of claim 37 wherein driving said switching device to a fully-off status, when said switching device is outside its dedicated active working area on the higher resistance side uses additional circuit elements, working as a signal-limiting function.

40. The method of claim 38 wherein said signal-limiting operation to drive said switching device to a fully-on status, when said switching device is outside its dedicated active working area on the lower resistance is implemented within the translinear amplifier.

41. A method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time and to compensate the temperature deviation of the capacitor switching device; comprising:

- providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on said capacitors in parallel, means for a set of translinear amplifier stages to produce said linear controls for said switching functions, means to linearly control the switching function for each of said continuous switching devices, means to compensate the temperature deviation of said switching device, means to individually provide the threshold points for each individual capacitor switching stage, means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages;

continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;

- linearly controlling the switching function for each of said continuous switching devices;

- compensating the temperature deviation of said switching;

- amplifying, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the threshold points of each amplifier stage to produce the linear control signal for said continually switching operation;

providing said threshold points for each individual capacitor switching stage; and supplying a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages.

42. The method of claim 41 wherein compensating the temperature deviation of said switching device is provided by feeding a modified reference voltage to said

translinear amplifier's output reference point, to mirror a temperature correcting signal into the control signal of said switching device.

43. The method of claim 42 compensating the temperature deviation of said switching device, uses a device of the same type as said switching device itself, to produce an exact equivalent of said temperature deviation.

44. A method to control the capacitance of a variable capacitor in a steady mode, but with predefined non-linear relation to the tuning voltage, through a tuning voltage and to achieve a high Q-factor at the same time; comprising:
providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on said capacitors in parallel, means to linearly control the switching function for each of said continuous switching devices, means for a set of translinear amplifier stages to produce said linear controls for said switching functions, means to individually provide the threshold points for each individual capacitor switching stage, means to provide a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages;
continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;
linearly controlling the switching function for each of said continuous switching devices;
amplifying, by the means of a translinear amplifier, the difference of the capacitance tuning voltage and the threshold points of each amplifier stage to produce the linear control signal for said continually switching operation;
providing said threshold points for each individual capacitor switching stage, producing non-linear instead of linear steps;
supplying a signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said translinear amplifier stages; and
providing a non-linear relation between said tuning voltage and said threshold points.

45. The method of claim 44 wherein individually providing said threshold points for each individual capacitor switching stage generates a set of reference values, one value for each capacitor switching stage.

46. The method of claim 44 wherein providing a non-linear relation between said tuning voltage and said threshold points is provided by specifically selecting the steps of said set of reference values in a way, to achieve said desired non-linear relation.

ABSTRACT

A voltage controlled variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, uses translinear amplifiers to control each switching element. Each translinear amplifier linearly switches from the fully off to the fully on state; a minimum number of switching stages (ideally only one) is in the mode-of-change at any one time with a minimum overlap. The arrangement achieves a nearly linear change of capacitance at linear tuning voltage change, while resulting in high Q-factor due to the low RDSon and high RDSoff of the fully switched stages. The invention eliminates temperature and voltage dependencies of other solutions like varactor diodes.

Fig. 9

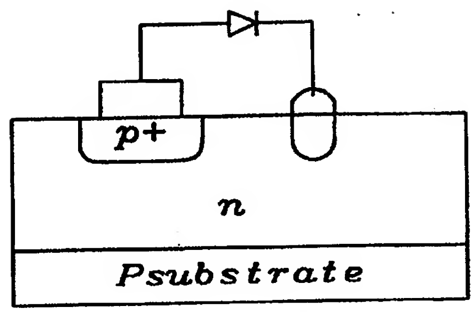


FIG. 1a – Prior Art

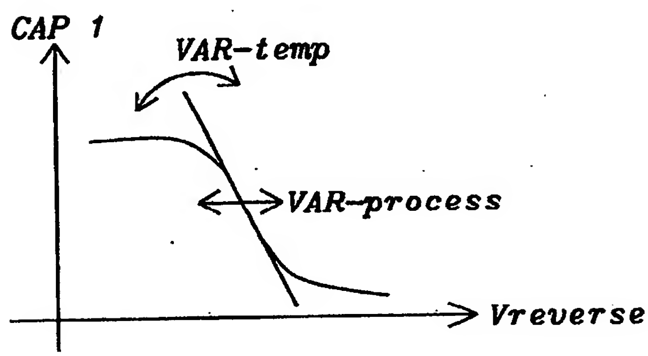


FIG. 1b – Prior Art

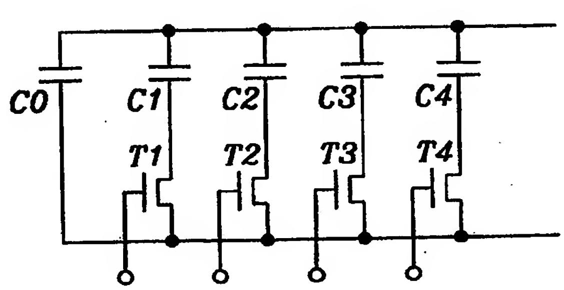


FIG. 2a – Prior Art

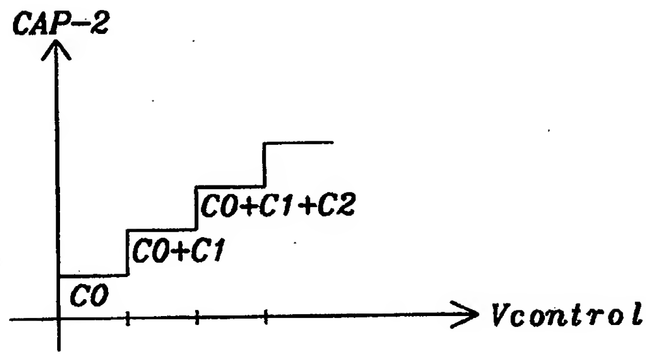


FIG. 2b – Prior Art

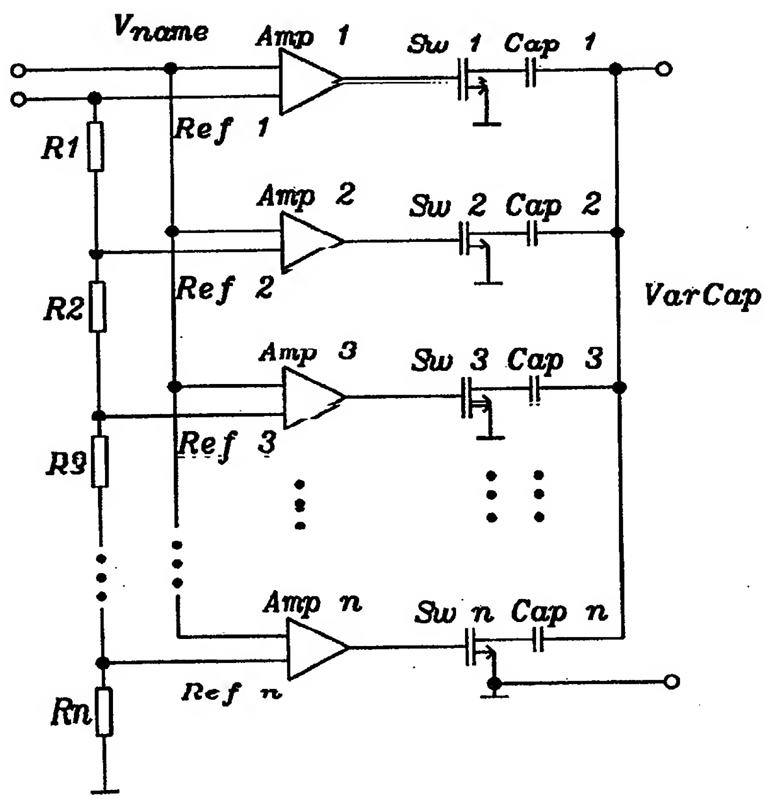


FIG. 3

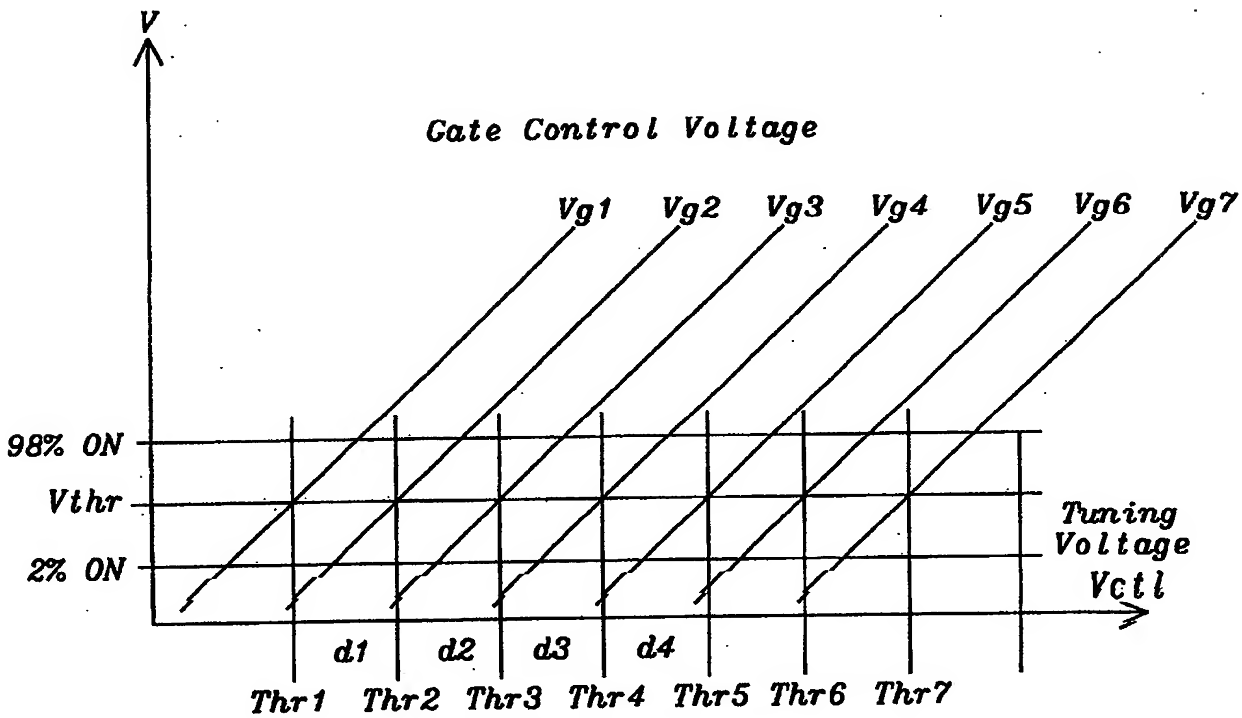

V
Gate Control Voltage
Vg1
Vg2
Vg3
Vg4
Vg5
Vg6
Vg7
98% ON
Vthr
2% ON
Tuning Voltage Vctl
d1
d2
d3
d4
Thr1
Thr2
Thr3
Thr4
Thr5
Thr6
Thr7

FIG. 4a

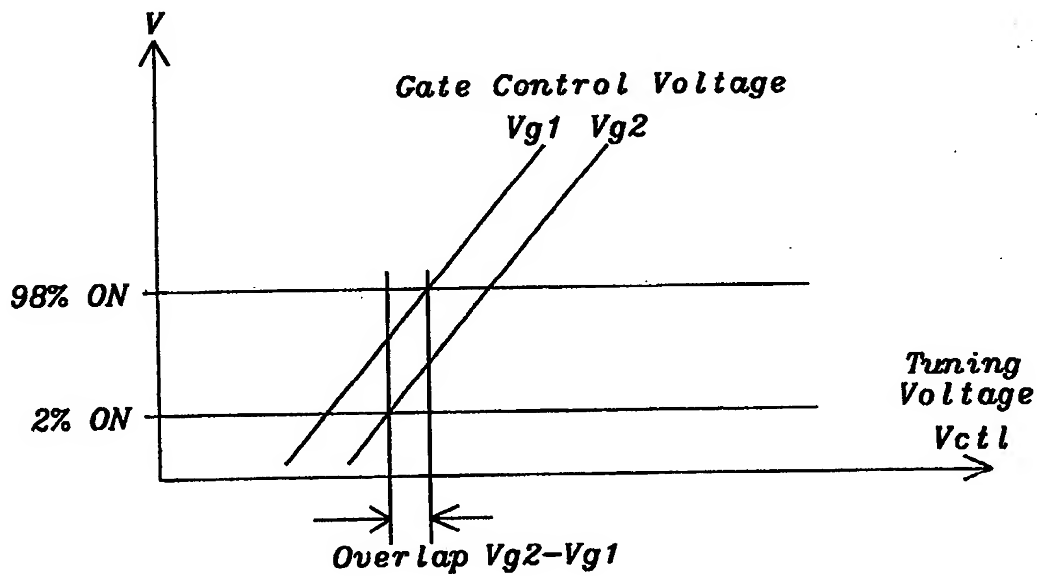

V
Gate Control Voltage
Vg1
Vg2
98% ON
2% ON
Tuning Voltage Vctl
Overlap Vg2-Vg1

FIG. 4b

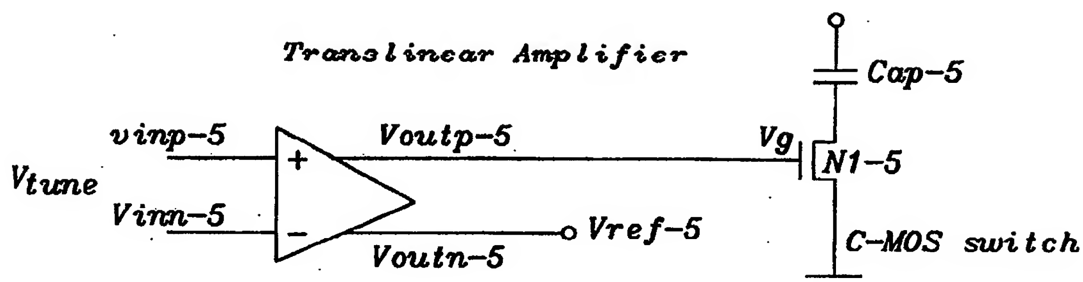

Translinear Amplifier
Cap-5
vinp-5
Voutp-5
Vg
N1-5
Vtune
Vinn-5
Vref-5
Voutn-5
C-MOS switch

FIG. 5

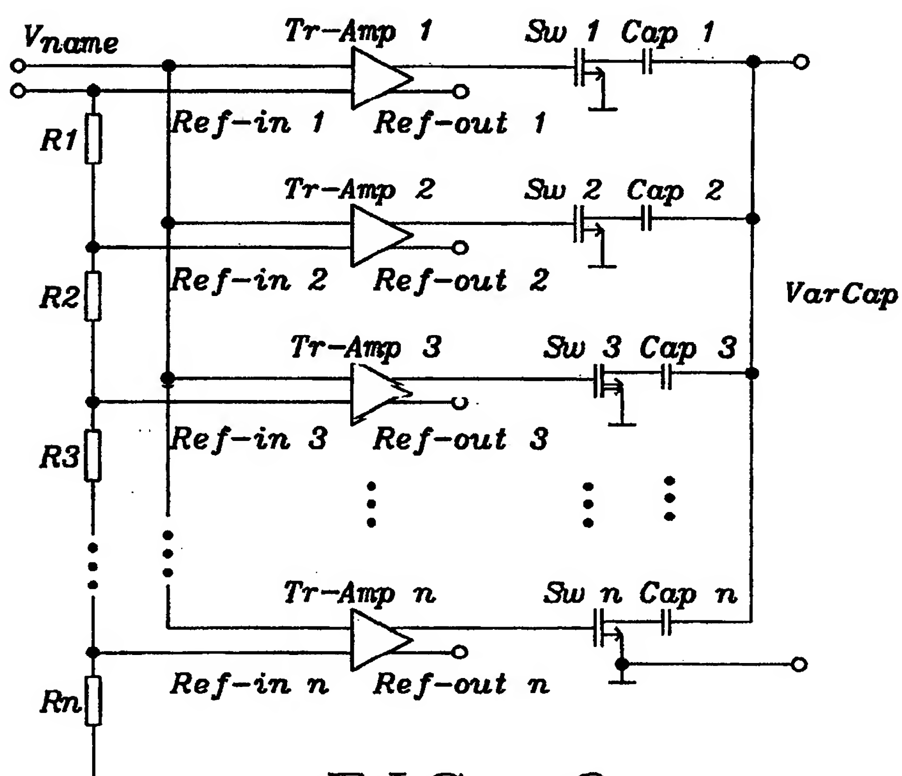

Vname
Tr-Amp 1
Sw 1
Cap 1
R1
Ref-in 1
Ref-out 1
Tr-Amp 2
Sw 2
Cap 2
R2
Ref-in 2
Ref-out 2
VarCap
Tr-Amp 3
Sw 3
Cap 3
R3
Ref-in 3
Ref-out 3
Tr-Amp n
Sw n
Cap n
Ref-in n
Ref-out n
Rn

FIG. 6

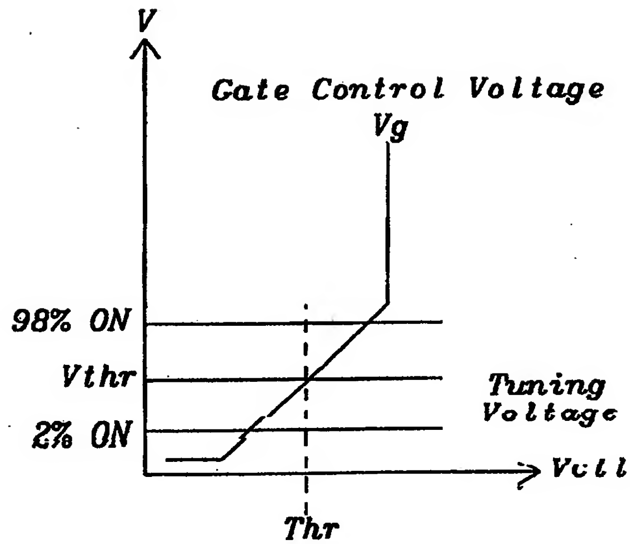

V
Gate Control Voltage
Vg
98% ON
Vthr
2% ON
Tuning
Voltage
Vctl
Thr

FIG. 7

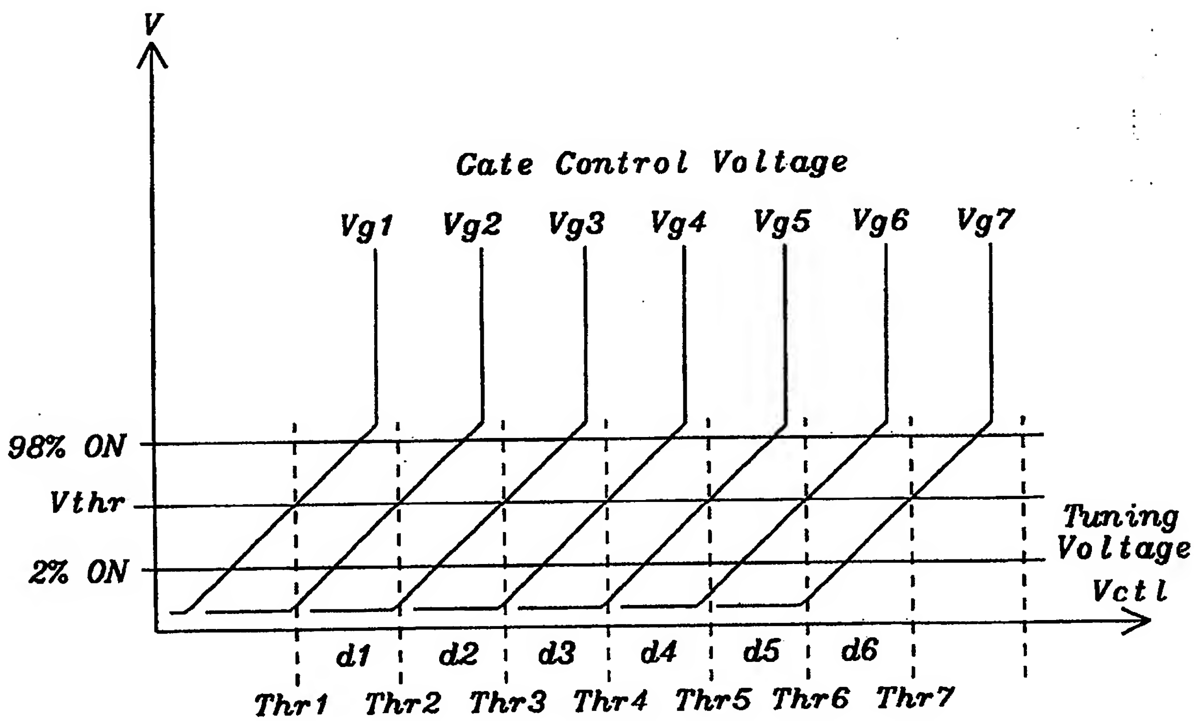
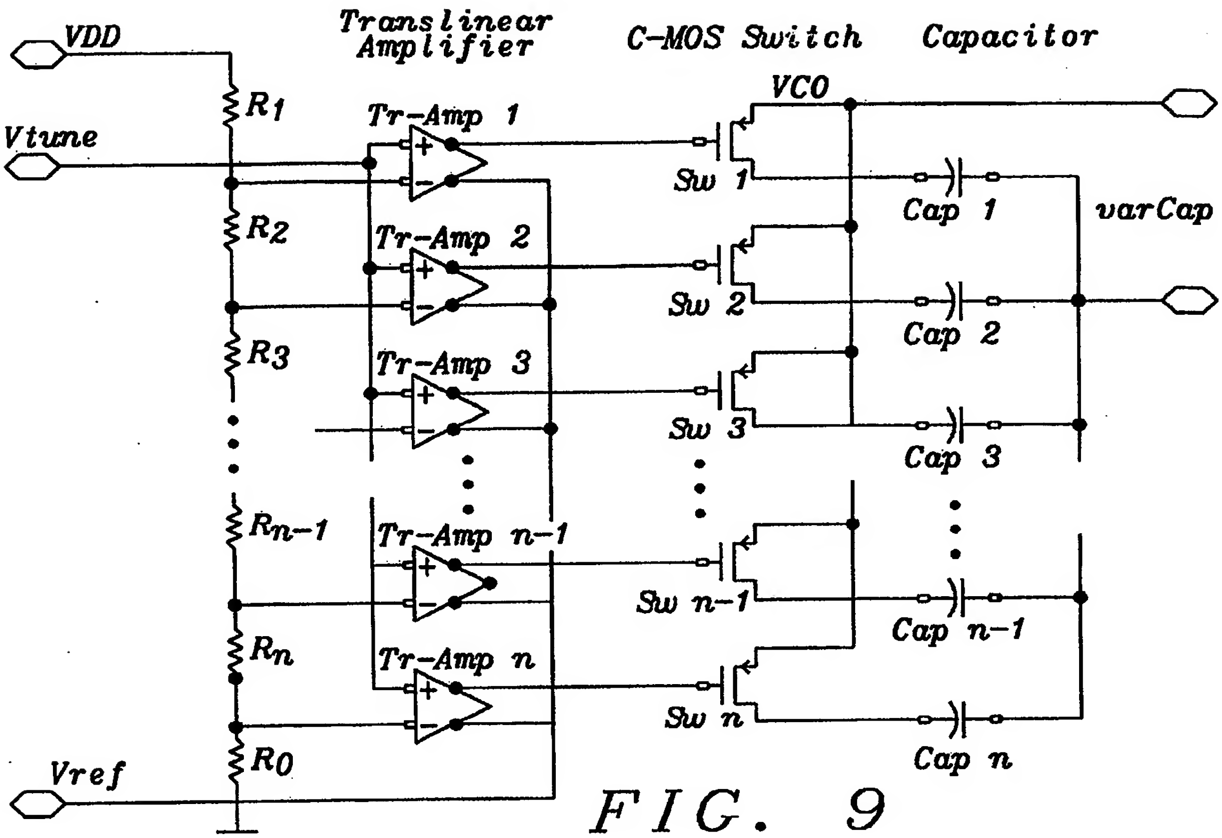
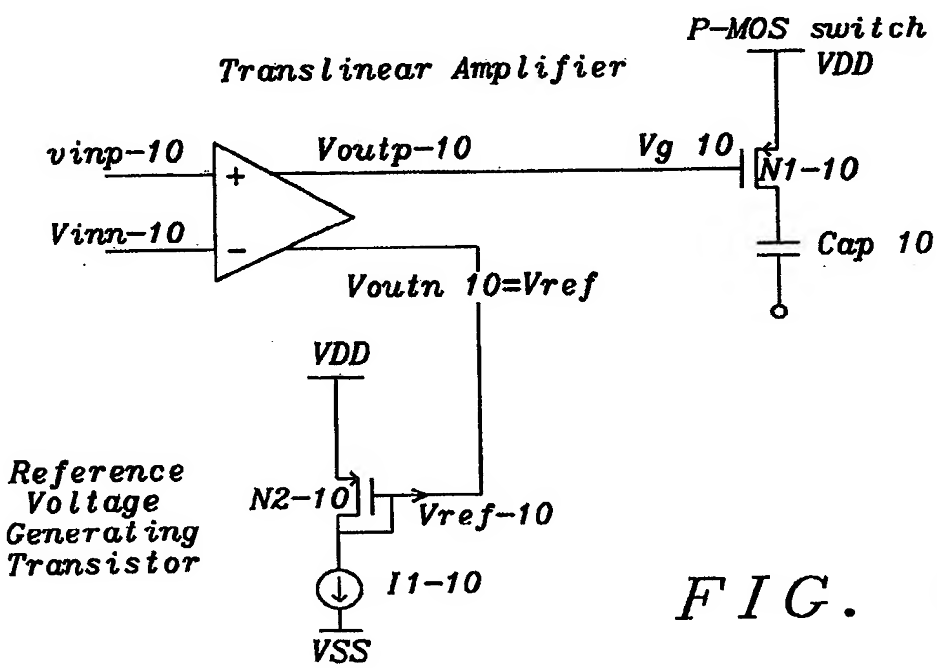

V
Gate Control Voltage
Vg1
Vg2
Vg3
Vg4
Vg5
Vg6
Vg7
98% ON
Vthr
2% ON
Tuning
Voltage
Vctl
d1
d2
d3
d4
d5
d6
Thr1
Thr2
Thr3
Thr4
Thr5
Thr6
Thr7

FIG. 8



VDD
Translinear Amplifier
C-MOS Switch
Capacitor
VCO
R1
Vtune
Tr-Amp 1
Sw 1
Cap 1
varCap
R2
Tr-Amp 2
Sw 2
Cap 2
R3
Tr-Amp 3
Sw 3
Cap 3
Rn-1
Tr-Amp n-1
Sw n-1
Cap n-1
Rn
Tr-Amp n
Sw n
Cap n
R0
Vref

FIG. 9



P-MOS switch
VDD
Translinear Amplifier
vinp-10
Voutp-10
Vg 10
N1-10
Vinn-10
Cap 10
Voutn 10=Vref
VDD
Reference Voltage Generating Transistor
N2-10
Vref-10
I1-10
VSS

FIG. 10

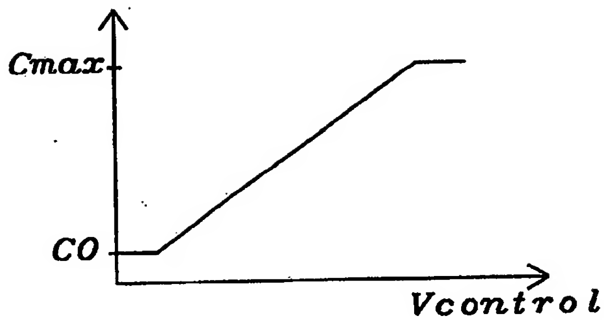


FIG. 11a

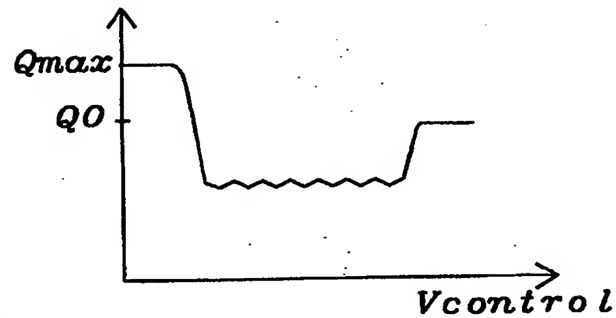


FIG. 11b

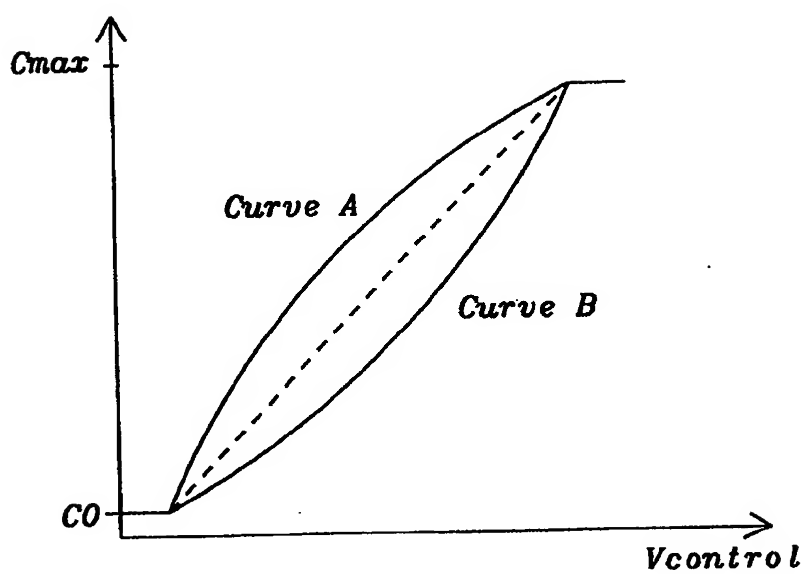


FIG. 12

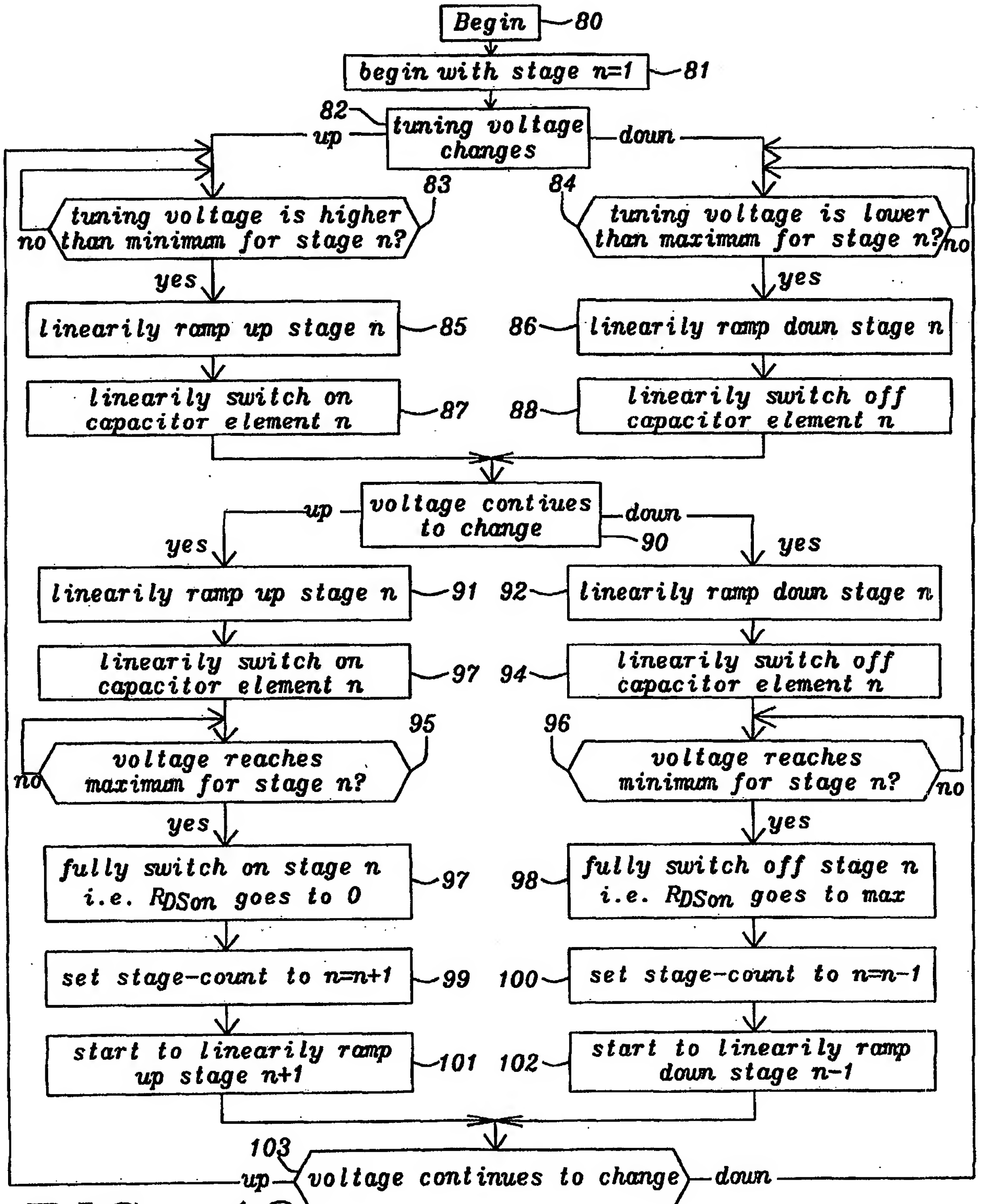


FIG. 13

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